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# Evaluation of Fire Models for Nuclear Power Plant Applications: Cable Tray Fires

## International Panel Report

Compiled by Monideep K. Dey, Guest Researcher

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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Compiled by Monideep K. Dey, Guest Researcher
*Fire Research Division*
*Building and Fire Research Laboratory*

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**U.S. DEPARTMENT OF COMMERCE**
*Donald L. Evans, Secretary*
**TECHNOLOGY ADMINISTRATION**
*Phillip J. Bond, Under Secretary of Commerce for Technology*
**NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY**
*Arden L. Bement, Jr., Director*

# Appendix G: Benchmark Analysis with JASMINE and CFAST, Stewart MILES, BRE, UK

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications

# Benchmark Exercise # 1 - Cable Tray Fires of Redundant Safety Trains

## Simulations using JASMINE and CFAST

**S.D. Miles**
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***SUMMARY***

*As part of its participation in the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications, BRE has made numerical predictions for Benchmark Exercise # 1 – cable tray fires of redundant safety trains. Trash bag and cable tray fires inside a switchgear room were modelled, with the main objective to ascertain the likelihood of thermal damage to a 'target' cable at various distances form the fire source.*

*BRE has performed simulations using a CFD model (JASMINE) and a zone model (CFAST). Results and analysis were presented at a meeting of the collaborative project in January 2001. This paper summarises the findings from the BRE simulations.*

*Due to the nature of the benchmark scenarios, both CFAST and JASMINE indicated that damage to the target cables was unlikely in all scenarios. However, some important observations were made, including the difficulty in modelling nearly-sealed rooms where the difference in pressure predicted by CFAST and JASMINE providing the most noticeable difference in the output from the two models. Other issues that were found to be important included the modelling/assessment of the heating of the target cables, and the influence of using different oxygen starvation criteria and fire source locations.*

## INTRODUCTION

In October 1999 the U.S. Nuclear Regulatory Commission and the Society of Fire Protection Engineers organised a planning meeting with international experts and practitioners of fire models to discuss the evaluation of numerical fire models for nuclear power plant applications. Following this meeting an international collaborative project was set up with a view to sharing knowledge and resources from various organisations and to evaluate and improve the state of the fire modelling methods and tools for use in nuclear power plant fire safety.

The UK Building Research Establishment (BRE) was represented at the next meeting of the collaborative project (ISPN, Pans, June 2000). The main outcome from this meeting was a finalised problem definition for a nuclear power plant fire scenario, to be used as a benchmark exercise for which the participating organisations would undertake numerical predictions and then compare results.

BRE's Fire and Risk Sciences (FRS) Division performed zone model (CFAST) and CFD (JASMINE) simulations of selected scenario cases from the benchmark exercise. Results and analysis were presented during the third meeting of the international collaborative project at the Electric Power Research Institute (EPRI), California in January 2001.

This paper summarises the CFAST and JASMINE simulations and findings. Following sections describing briefly the fire models used, there is a section highlighting the main results and analyses.

## CFAST DESCRIPTION

CFAST is one of the most widely used zone models, available from the National Institute of Standards and Technology (NIST), USA. It is the main component of the program suite FAST, which is controlled through a graphical user interface. CFAST/FAST version 3.1.6 was used in the current study, which is the most recent complete version to be released.

CFAST is a multi-room zone model, with the capability to model multiple fires and targets. Fuel pyrolysis rate is a pre-defined input, and the burning in the compartment is then modelled to generate heat release and allow species concentrations to be calculated. For most applications CFAST is used as a conventional two-zone model, whereby each compartment is divided into a hot gas upper layer and a cold lower layer. In the presence of fire, a plume zone/model transports heat and mass from the lower to upper layer making use of the McCaffrey correlation [1]. Flows through vents and doorways are determined from correlations derived from the Bernoulli equation. Radiation heat transfer may be included using an algorithm derived from that of Siegel and Howell [2]. Other features of CFAST of relevance to the benchmark exercise include a one-dimensional solid phase heat conduction algorithm employed at compartment walls and targets and network flow model for mechanical ventilation.

Publications available on the NIST website (www.nist.gov) [3,4] provide a comprehensive description of CFAST and the models employed. A summary of Comparison with experimental measurements is provided also.

## JASMINE DESCRIPTION

JASMINE is a CFD fire code that has undergone continual development at the BRE over nearly 20 years. It simulates fire and smoke movement in three-dimensions, for steady state and time-dependent applications. Version JASMINE 3.1 was used in this benchmark exercise.

JASMINE is a finite-volume CFD code, employing a variant of the SIMPLE pressure-correction scheme on a structured, Cartesian mesh. The program can model single and multiple compartment enclosures with arbitrary openings (doors, windows and vents), obstructions, fire/heat sources and mechanical ventilation systems. External wind profiles, static pressure boundaries and symmetry planes may be specified.

A modified, enhanced version of an early PHOENICS code provides the core pressure-correction solver. Turbulent closure is by a k-ε model using the standard constants and additional buoyancy source terms. Standard wall functions for enthalpy and momentum describe the turbulent boundary layer adjacent to solid surfaces. A suite of sub-models for combustion, radiation, data analysis etc has been added as part of the code development.

A scenario may be set-up using the graphical user interface (JOSEFINE), which allows the user to define the geometry and boundary conditions and view the results with a graphical post-processor. The results may be viewed also with the commercial CFD post processor FIELDVIEW. A detailed summary text file is generated, containing convergence information, analysis data etc.

JASMINE has been validated against data from pre-flashover fire experiments inside domestic size rooms, atria, tunnels, hospital wards and other enclosures. More recently it has been validated against data from post-flashover fire tests also. Further details are provided in the validation section.

### Modelling Details

Mathematical details of the differential-integral equations describing the fluid flow processes may be found elsewhere, see for example [5]. In summary, the equations describing the fluid dynamics of Newtonian fluids (which includes most common fluids such as air and water) are the Navier-Stokes equations for momentum and mass conservation and the related advection-diffusion transport equation describing conservation of other properties such as energy and species concentration. These equations, together with equations of state for density and temperature, describe very accurately the physics of Newtonian fluids.

CFD models approximate the underlying equations with a coupled system of algebraic equations that are solved numerically on a discrete mesh or grid. This yields predictions for velocity, pressure, temperature etc at each mesh point in space and time. JASMINE, in common with most other CFD fire models, employs the finite volume method [6,7], in which the differential equations are first transformed into an integral form and then discretised on the control volumes defined by the mesh.

JASMINE solves a time/ensemble-averaged form of the Navier-Stokes and transport equations, where the turbulent fluctuations are not modelled explicitly, but instead are 'incorporated' into the solution by a 'turbulence model'. The particular model used in JASMINE is the industry standard, $k$-$\varepsilon$ model [8], which employs the eddy viscosity assumption in which the effect of turbulence is included as an additional 'turbulent viscosity'. Additional source terms are included in the $k$-$\varepsilon$ model to account for the effects of buoyancy [9].

The ensemble-averaged Navier-Stokes and transport equations, coupled with an equation of state (ideal gas law) and the various sub-models for the fire physics, defines the equation set in JASMINE. This is discretised and solved numerically on a structured three-dimensional grid using the SIMPLEST scheme, a variant of the SIMPLE pressure-correction scheme [7,10]. Convection terms are discretised with the first-order 'upwind' scheme and time advancement is by the first-order, fully implicit, backward Euler scheme. Standard wall functions for enthalpy and momentum [8] describe the turbulent boundary layer adjacent to solid surfaces.

Combustion is generally modelled using an eddy breakup assumption [11] in which the fuel pyrolysis rate is specified as a boundary condition, and combustion is then calculated at all control volumes as a function of fuel concentration, oxygen concentration and the local turbulent time-scale (provided by the $k$-$\varepsilon$ model). Simple one-step, infinitely fast chemical reaction is assumed. The eddy breakup model is appropriate for turbulent diffusion flames characteristic of fire, where the rate of reaction is controlled by the comparatively slow mixing of fuel with oxygen. Complete oxidation of the fuel is assumed when sufficient oxygen is available, and therefore predictions of carbon monoxide are not provided by this approach.

Radiant heat transfer is modelled with either the six-flux model [12], which assumes that radiant transfer is normal to the co-ordinate directions or the slower, but potentially more accurate, discrete transfer method [13]. Local absorption-emission properties are computed using Truelove's mixed grey-gas model [14], which calculates the local absorption coefficient as a function of temperature and gas species concentrations and, if available, soot concentration also.

Density is defined from the equation of state, and gas temperature is calculated from the definition of enthalpy, in which specific heat is itself a function of temperature and species concentrations. Thermal conduction into solid boundaries is approximated by a quasi-steady, semi-infinite one-dimensional assumption.

## Code Validation

JASMINE has been validated against experimental measurement for a range of scenarios, ranging from small enclosure fire experiments to large, fully developed fires in tunnels and offshore structures. Some of the more important validation cases are referenced below.

<u>The Steckler experiments</u> [15]. In these experiments steady state mass flow rates, velocity profiles and temperatures associated with a burner at various locations inside a 2.8 m x 2.8 m x 2.18 m compartment with a single doorway opening were measured. Good agreement was found for the doorway flow rates, with the CFD model capturing the influence of plume lean on the entrainment process.

The Lawrence Livermore experiments [16]. A series of steady state experiments were performed with a spray pool fire inside a 6 m x 4 m x 4.5 m nuclear test cell with mechanical ventilation. Good agreement was obtained for temperatures inside the test cell, and the prediction of fire-induced pressure rise was reasonably close to the measured value.

Hospital ward experiments [17]. An experiment was performed involving a burning PU-foam mattress in a ward of dimensions 7.3 m x 7.9 m x 2.7 m. Pre-fire steady condition, driven by the heat released from a set of wall radiators, and the subsequent transient fire phase were simulated. Good temperature agreement was achieved, and good species ($CO_2$) agreement at head height also. However, there was some discrepancy in $CO_2$ at bedside height.

Sports stadium [18]. Simulations were made of fire tests performed in a 1/6th-scale physical model of a proposed sports stadium. Comparisons were made for temperatures at thermocouple tree locations, which showed good agreement. Some discrepancy at ceiling level was attributed to the approximate 'staircase' representation of the dome shape.

Zwenbera railwav tunnel experiments [19,20]. Predictions made by TUNFIRE, the tunnel specific version of JASMINE, were compared to measurements from a series of fire tests in the disused Zwenberg railway tunnel in Austria. The tunnel is 390 m long wit a 2.18% gradient. Steady state scenarios involving natural and forced longitudinal ventilation with fires of approximately 20 MW were modelled. Predictions of the temperature and species downstream of the fire source were in good agreement with measurement. However, the need for further model development in the treatment of radiation and heat transfer in the vicinity of the fire was highlighted.

Memorial Tunnel experiments [21]. The decommissioned Memorial Tunnel in the USA was used for an extensive set of fire tests involving natural, longitudinal and transverse ventilation. A selection of the longitudinal ventilation tests, involving pool fires from 20 to 100 MW, was modelled with TUNFIRE. The transient simulations captured the main features of the tests, predicating the performance of various jet fan configurations reasonably well. Some discrepancy was found in the pre-ventilation stage where the smoke layer dropped to ground level more quickly in the simulations compared to the tests.

Channel Tunnel shuttle waaon tests [22]. As part of the safety study for the Channel Tunnel, JASMINE was validated against fire experiments inside a car shuttle wagon. It was shown that by considering properly the mechanical ventilation system and the boundary heat losses reasonably good agreement could be achieved for temperature and gas species.

LBTF tests [23]. An eight-storey, steel framed building, constructed at BRE's Cardington Hanger, provided an ideal opportunity to perform full-scale fire tests. The 8.4 m high atrium and part of the first floor were used in the study of fully-ventilated fires up to 5 MW in size. Predictions of smoke layer depth and temperature matched experimental measurement reasonably closely, as did the entrainment rates.

Post-flashover compartment fire tests [24]. A series of fully developed, ventilation-controlled fire tests was sponsored by the European offshore industry to validate zone and CFD models. Tests involving pool fires up to 80 MW inside single opening enclosures were modelled with JASMINE. Good agreement was found in the vent flow rates and temperatures. Furthermore, the simulations captured the oxygen depletion process correctly. The main discrepancy was in the temperatures and fluxes at the back of the compartment. attributed in part to the complexity of the wall lining behaviour, which involved the steel sheeting becoming partly detached during the tests.

CIB round robin activity [25]. The Commission of the International Council for Research and Innovation in Building and Construction (CIB) co-ordinated a series of round robin fire model validation exercises in which participants made 'blind' predictions for fire tests in the knowledge of only a limited amount of information (geometry, thermal properties, fire pyrolysis rate). **JASMINE** simulations were made for a compartment (7.2 m x 7.2 m x 3.6 m) with a 'letter-box' opening and two crib fire sources. Good agreement was found for species predictions, and reasonable agreement for temperatures. Predicted incident wall fluxes were noticeably lower than those 'estimated' from the measurement data, attributed in part to the quasisteady heat conduction treatment used in the simulations.

Balconv spill plume tests [26]. As part of a wider study into the entrainment processes associated with spill plumes, **JASMINE** simulations of various $1/10^{th}$-scale experiments were performed. Predicted and measured entrainment rates were in reasonable agreement. An important conclusion was that grid refinement did have an important influence on the predicted entrainment rate.

Sprinkler model validation [27]. As part of the development of a sprinkler model for **JASMINE,** simulations were undertaken of a full-scale fire test where the influence of the water spray on gas temperatures and velocities at ceiling level was investigated. Reasonable agreement was found, and areas of further improvement identified.

## BENCHMARK EXERCISE

### Problem Definition

Following publication of the specification for the benchmark exercise # 1, BRE has undertaken CFD (JASMINE) and zone model (CFAST) predictions for selected scenario cases. The benchmark exercise is described in Appendix A.

Table 1 shows the scenario cases modelled by BRE. Due to the long duration of the Part II scenarios (80 minutes), the CFD (JASMINE) simulations were undertaken for between 20 and 45 minutes only (depending on the case). This was sufficiently long to investigate the main features of each scenario, and allowed more cases to be undertaken with the available computing resource. Whereas individual JASMINE simulations were undertaken for each Part I case, some of the Part II cases were 'doubled up' in that a CFD solution was used to investigate more than one case. This was due to some cases differing only in the location of the target cable, which itself did not influence the CFD solution, *i.e.* one CFD solution was used to predict the thermal damage to multiple target locations.

| Numerical Model | Scenarios Modelled |
|---|---|
| JASMINE | Part I: base case, case 1 and case 4<br>Part II: base case and cases 1,2, 9,10,11,12 & 13 |
| CFAST | Part I: all cases<br>Part II: all cases |

While the problem specification was followed as closely as possible, some user interpretation was required, in particular in respect to the target description and the treatment of radiation. Most simulations were completed prior to the third project meeting, and the findings were presented at that meeting. Some further simulations have been performed since, looking at the effect of mechanical ventilation with CFAST and the prediction of pressure in the door-crack scenarios with JASMINE.

In CFAST, heat transfer to a rectangular target object, orientated in a particular direction, can be modelled using a one-dimensional equation. The simulations showed that the choice of target orientation could have a significant influence on the size of the incident heat flux. JASMINE also allows heat transfer to solid objects to be modelled using a semi-infinite, quasi-steady approximation. For the current work, however, an assessment of the likelihood of target cable damage was based on the local gas temperature and mean radiation flux. This will in general provide a conservative approach, over-predicting the thermal hazard.

For the CFAST simulations radiation from the fire plume was incorporated, as specified, by reducing the fire size by 30%. For the JASMINE simulations a six-flux radiation model was employed, and rather than defining the radiation loss explicitly it was predicted by the solution of the CFD and radiation models. Some later simulations investigated the effect of using a fixed radiation loss of 30% and no radiation model.

The two-zone assumption was used for all the CFAST simulations. A constrained fire was assumed, which allowed for oxygen availability to control the rate of heat release from the pre-defined pyrolysed fuel. As stipulated in the benchmark specification, a 30% radiative loss was included. Although the wall and ceiling thermal properties were specified exactly, the separate door properties were not included. To investigate the effect of orientation on the predictions of target surface temperature, two normal directions were considered, namely facing towards the ceiling and towards the floor. The ceiling jet sub-model was used.

The JASMINE simulations employed between 124,000 and 175,000 control volumes, resolving the vertical extent of the door crack with two control volumes. An eddy break-up combustion model was used, which allowed the oxidation of the pre-defined pyrolysed fuel to be calculated as a function of oxygen concentration and local turbulent mixing. The six-flux radiation model, combined with Truelove's emissive power model, was used in the majority of simulations, allowing the radiation losses from the plume and hot gas layer to be calculated with reasonable accuracy. However, to compute fluxes to target cables with greater accuracy would have required the computationally more expensive discrete transfer model. Soot formation and oxidation was not modelled. Although not generally employed in the JASMINE combustion model, a oxygen cut-off was applied in the majority of simulations, using a figure of 12% as requested.

Both JASMINE and CFAST showed that for Part I sufficient oxygen was available for continual combustion in all cases, i.e. the open doorway and door crack cases. The 12% LOL was not reached in either set of simulations. Both models indicated that target cable damage would be very unlikely due to only a modest rise in gas temperature. Figures 1 and 2 show CFAST and JASMINE temperature predictions for the base case and cases 4 and 5 of Part I. Whereas the CFAST values are for the upper layer in the two-zone approximation, the JASMINE temperatures are for a location just below the centre of the ceiling. This will account in part for the difference in predicted values for CFAST and JASMINE, since the CFD model does not consider an average layer/zone temperature. A further point to note is that JASMINE predicted a slight increase in temperature in the presence of mechanical ventilation, which was not shown in the CFAST simulations. Additional, forced airflow will effect the flow pattern in the plume and upper layer, and this is not captured by a zone model. Figure 3 illustrates the effect that mechanical ventilation has on the plume shape in the JASMINE simulations.

A significant finding from the CFAST simulations was that the target orientation could have an important bearing on the incident flux, and resultant target temperature. By facing the target downwards the incident flux was in some instances more than double that obtained when the target faced upwards, as illustrated in Figures 4 and 5. If the target had been directed directly towards the fire, i.e. at an oblique angle, then the incident flux and heating of the cable would most probably been higher still.

Figure 6 shows target radiation fluxes estimated from the JASMINE simulations, where because the target was not modelled explicitly, an average directional flux has been taken. Whereas for case 1 the flux levels are comparable between CFAST and JASMINE, for the other cases examined with JASMINE the similarity is much less. A significant factor here is that JASMINE models radiation emission and absorption from the gas layer ($CO_2$ and $H_2O$), which may be an important transfer mechanism.

As shown in Figures 7-9, both models produced similar flow rates across the doorway for the open doorway scenario (case 4). This scenario represents the classic enclosure fire for which both zone and CFD models would be expected to give similar results.

The most significant difference between the JASMINE and CFAST predictions for Part I was in the pressure predictions for the door crack cases, with CFAST predicting significantly higher pressure build up inside the room. Furthermore, whereas JASMINE predicted outflow form the door crack throughout the duration of the scenario (10 minutes), CFAST predicted a period of moderate inflow after the initial pressure build-up had been dissipated due to venting of gases through the door crack. Figures 10 and 11 show the pressure predictions for CFAST and JASMINE, without (base case) and with (case 5) additional mechanical ventilation. The outflow and subsequent inflow predicted in the CFAST simulation can be seen in Figures 9 and 10.

On initial examination, the pressures predicted by CFAST for the door crack cases (peak value approximately 2000 Pa) seem perhaps too high, whereas the JASMINE values (of the order 50 Pa) seem more reasonable for a compartment fire scenario. While the 'background' pressure level within a sealed compartment is generally not important from the point of modelling fire development (although structural/mechanical considerations may be important), it may be more significant when venting through small orifices is included. Here, the difference in pressure between the inside and outside will have a strong bearing on the flow rate through the opening.

JASMINE adopts the usual assumption adopted in 'low speed' CFD models and treats the air as weakly compressible, **i.e.** density is defined as a function of temperature and species concentration. The coupling between pressure and density, included in 'high speed' fully compressible models, is ignored. Whether this is important for 'nearly sealed' compartment fire simulations is not clear. CFAST does not solve for conservation of momentum, and the bearing this may have ***on*** the door crack scenarios is also not clear.

Further JASMINE analysis of the door crack scenario for Part I has been undertaken since the third meeting of the collaborative project. By defining a 30% radiation loss explicitly, and switching off the radiation model, the period of over-pressure inside the room was followed by a period of under-pressure and associated inflow of outside air. This behaviour was predicted by CFAST, albeit with significantly higher over-pressure. Interestingly, using a volume heat source instead of a combustion model resulted in a higher over-pressure (approximately 120 Pa peak), and again a subsequent period of under-pressure and air inflow. The effect of replacing the door crack with a square opening of equivalent area was investigated, producing a similar result but, as expected, a reduced level of over-pressure. Figure 12 shows the JASMINE pressures for the original base case and also the above modified scenarios. Figure 13 shows that a period of inflow follows, **as** expected, if the pressure inside the room decreases below ambient.

Clearly the thermodynamics of fire within a 'nearly sealed' compartment is a complex issue that has received much less attention by the fire safety community than fire inside enclosures with at least a moderate level of venting to the outside. Further work in this area is recommended.

For Part II, both JASMINE and CFAST indicated again that target cable damage was unlikely. Oxygen depletion was a significant feature in the door crack cases for Part II, with both models predicting oxygen consumption after about ten minutes. Figure 14 shows the upper layer temperatures predicted by CFAST for the base case and cases **3** and 6 with the larger fires. Figure **15** shows the JASMINE gas temperatures at the target locations for the door-crack scenarios with the smaller fire. The peak temperature at the target location for the base case is similar to the peak upper layer temperature predicted by CFAST. The actual LOL value was not very significant, with the effect of reducing the **LOL** to zero being to allow combustion to continue for a while longer before stopping due to a lack of available oxygen.

The effect of placing the burning cable tray at floor level was investigated with CFAST, and this did have an influence on the level thermal hazard predicted. In particular, with the larger (3 MW) fire the effect of more combustion occurring before the layer height reached the level of the fire source was an increased upper layer temperature. Figure **16** shows that, combined with a 0% **LOL** value, this resulted in predicted target surface temperatures that might signify damage. Note that the difference in peak temperature for the three cases is most likely a numerical effect of the model.

However, for both CFAST and JASMINE, a more sophisticated treatment of heat transfer to the target cable, and the subsequent conduction of heat into the cable, would be required in order to obtain more precise estimates of cable temperature and thermal damage. It is likely that the main contributing factor to cable damage for the scenarios like those of Part II would be due to radiative heat transfer from the flaming region, which in cases where the fire source is close to the target cable could be sufficient to cause thermal damage. However, as posed, the Part II scenarios did not allow for this process to be addressed realistically. This was due to the burning area of the fire source being approximated as the entire length of the source (burning) cable, which obviously reduces drastically the intensity of the fire source during the fire growth phase.

In respect to the target orientation issue in CFAST, it was found for Part II that upward facing targets were exposed to greater thermal fluxes than downward facing ones. This was in contrast to Part I, and indicated the importance of this aspect of user interpretation in setting up a scenario.

For Part II, the main discrepancy between CFD and zone model predictions was again in the level of over-pressure in the door crack cases. However, the discrepancy was less than in Part I. Figures **17** and 18 show that the peak over-pressure in the base case was approximately 300 Pa with JASMINE and **750** Pa with CFAST. Furthermore, the CFAST pressure predictions for the door crack cases in Part II were not entirely convincing. As illustrated in Figure 19, placing the cable tray fire source in the base case at floor level resulted in the peak over-pressure increasing from 750 Pa to nearly 5000 Pa, which seems out of proportion compared to the much more modest increase in temperature. Moreover, the peak pressure in excess of 12000 Pa obtained when locating the **3** MW cable tray fire at floor level is certainly surprisingly high.

Cases 9 and 10 of Part II, involving combinations of mechanical ventilation and open doorway conditions, were undertaken with JASMINE. However, in Part II it was not possible to obtain sensible CFAST results with mechanical ventilation.

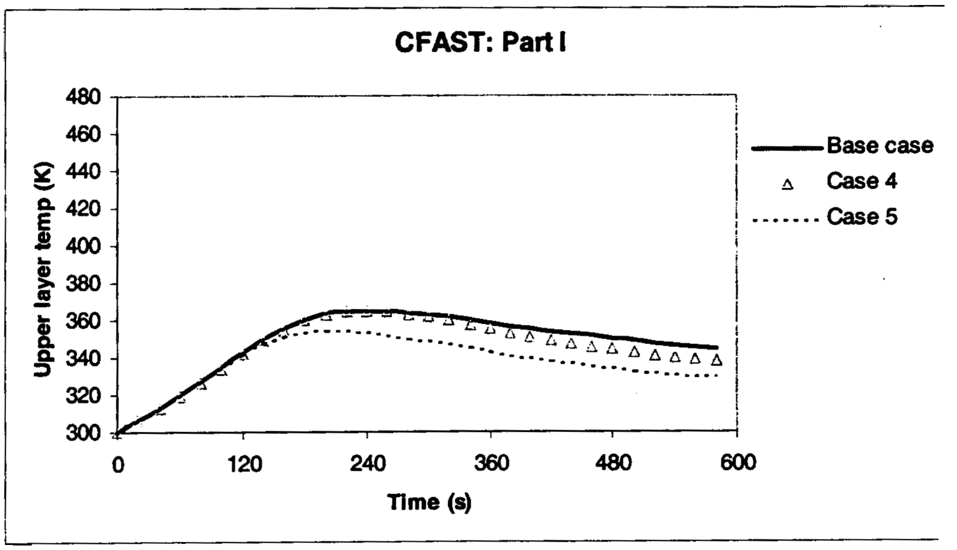



Figure 1 CFAST predictions of upper layer temperatures in Part I

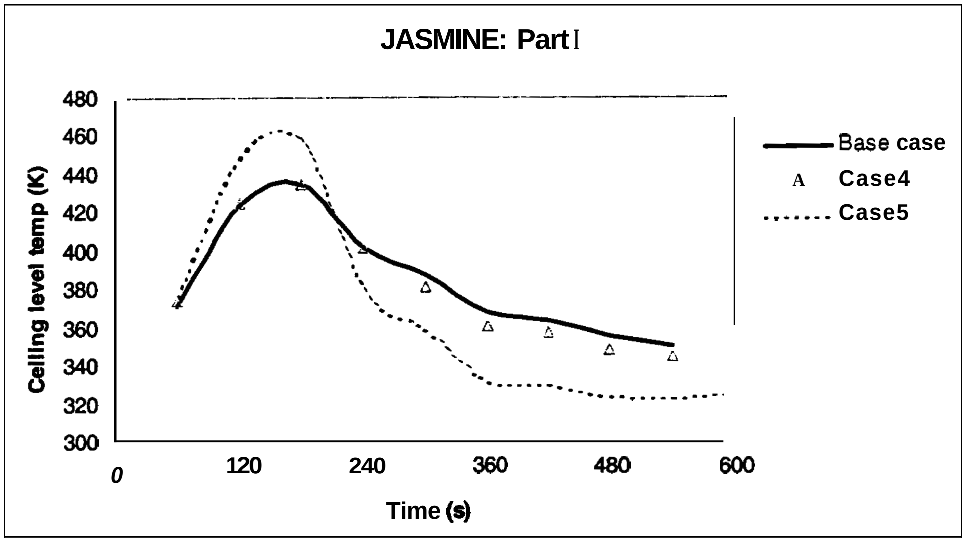
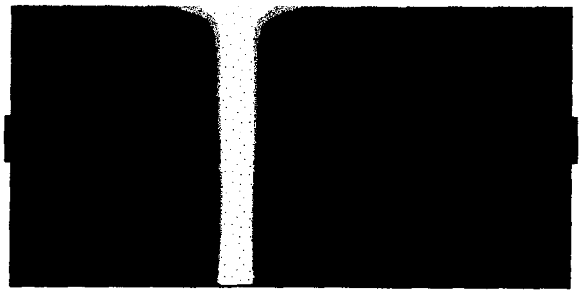
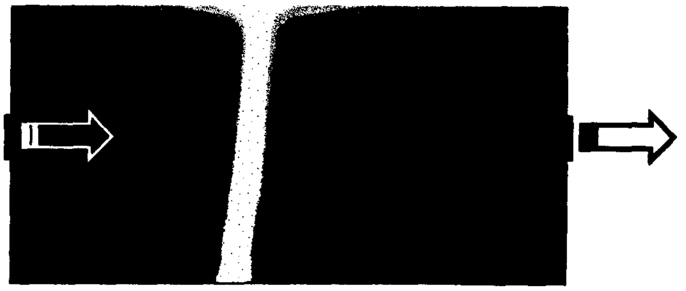



Figure 2 JASMINE predictions of ceiling level temperatures in Part I



Part I base case – no mechanical ventilation



Part I case 5 - with mechanical ventilation

Figure 3 JASMINE plume shape at 180 s with and without mechanical ventilation

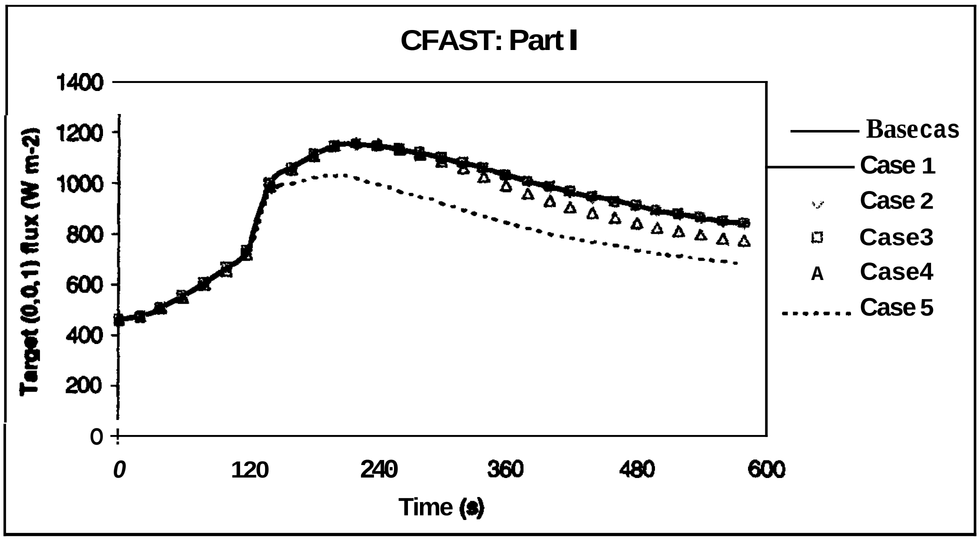



Figure 4 CFAST predictions of fluxes to upward facing targets in Part I

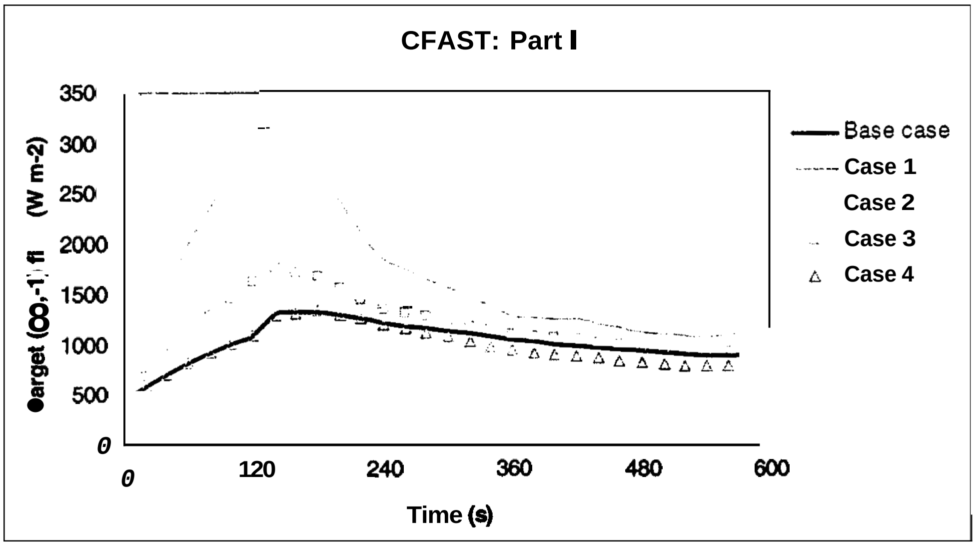



**Figure 5** CFAST predictions of fluxes to downward facing targets in Part I

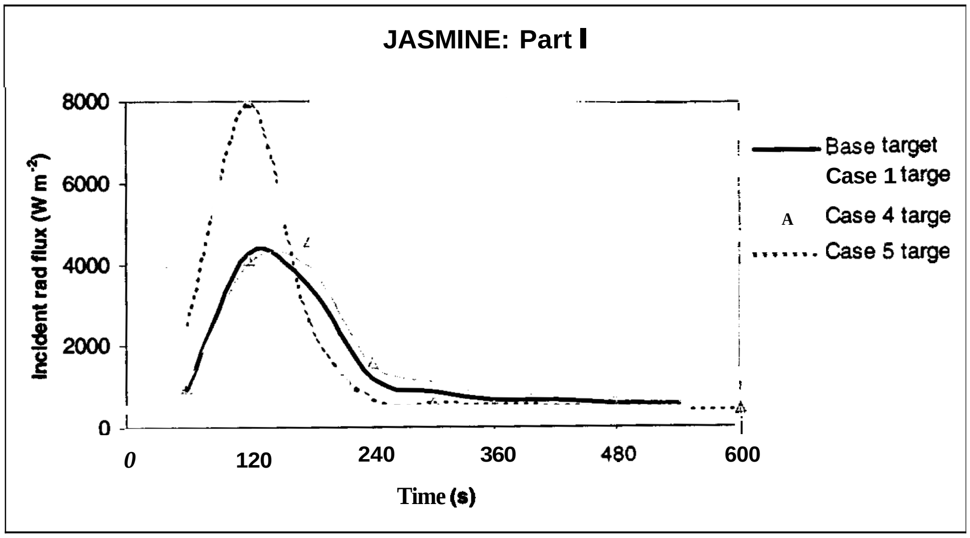



**Figure 6** JASMINE predictions of incident fluxes in Part I

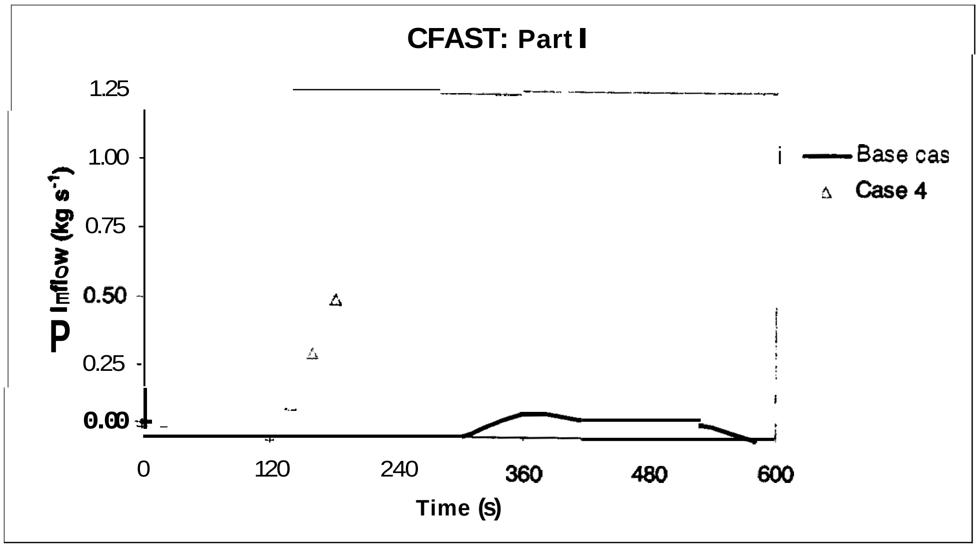



Figure 7 **CFAST** predictions of inflow rates in Part I

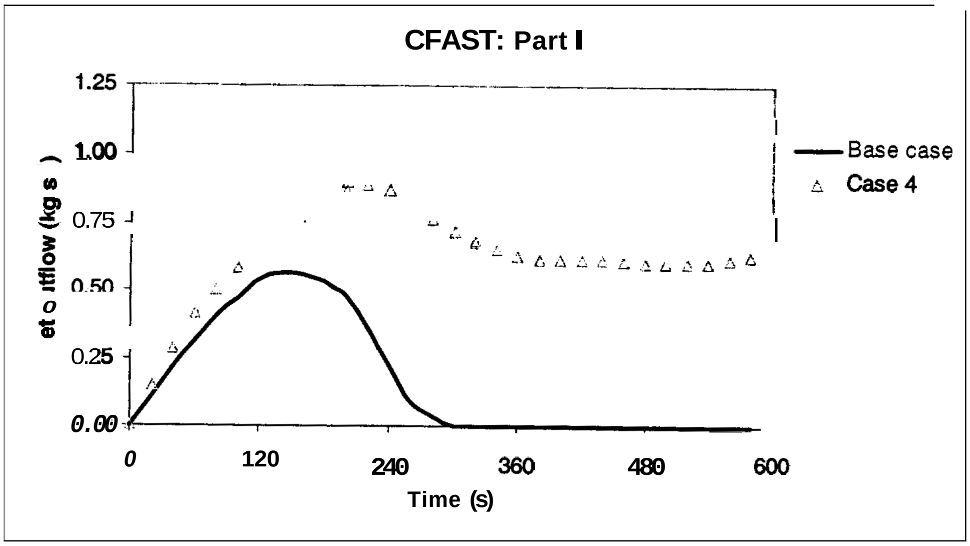



Figure 8 **CFAST** predictions **of** outflow rates in Part I

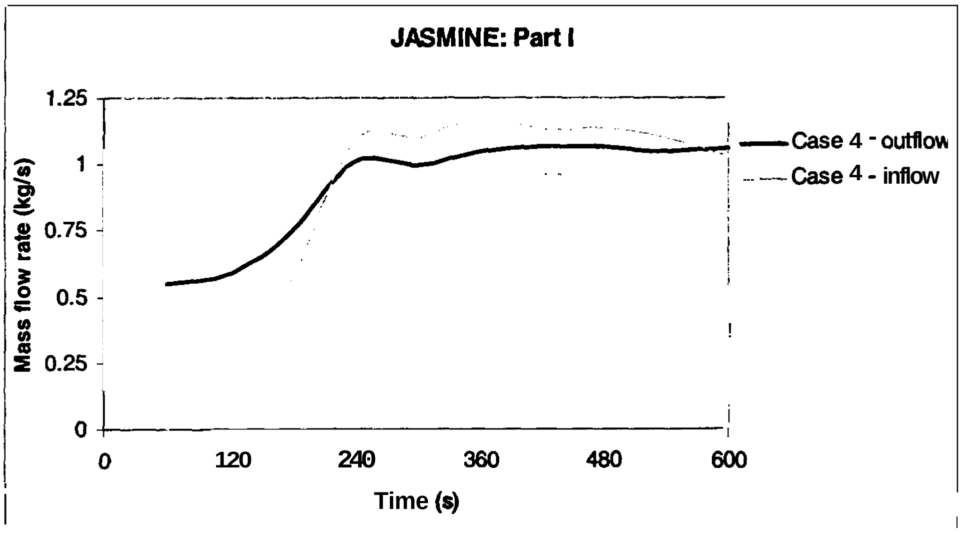



Figure 9 JASMINE predictions of inflow/outlow rates in Part I

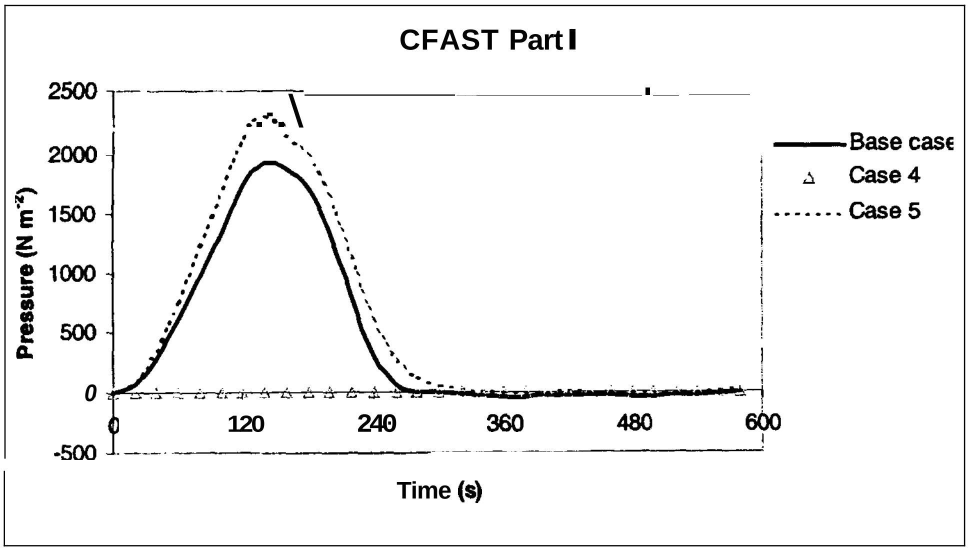



Figure 10 CFAST predictions of pressure in Part I

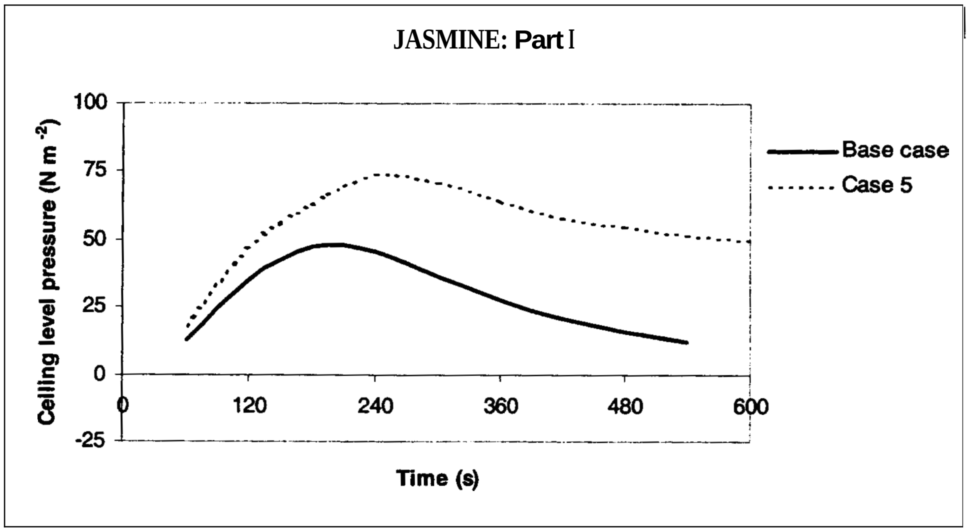



Figure 11 JASMINE predictions of pressure in Part I

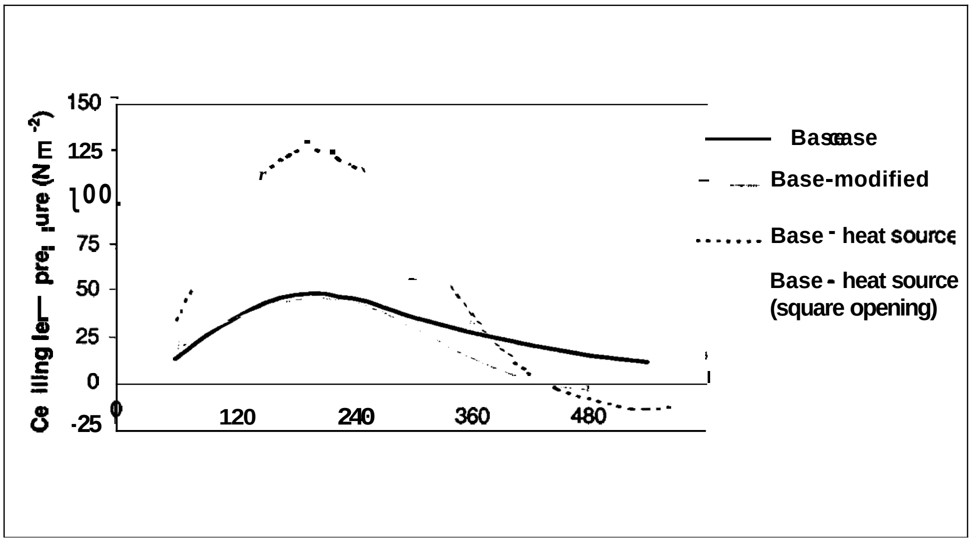



Figure 12 JASMINE predictions of pressure in Part I

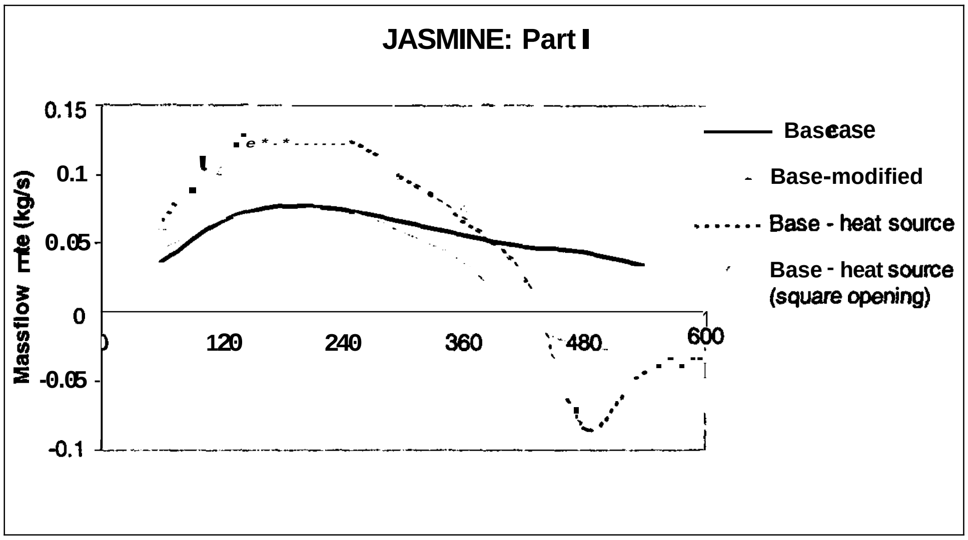



Figure 13 JASMINE predictions of inflow/outflow in Part I

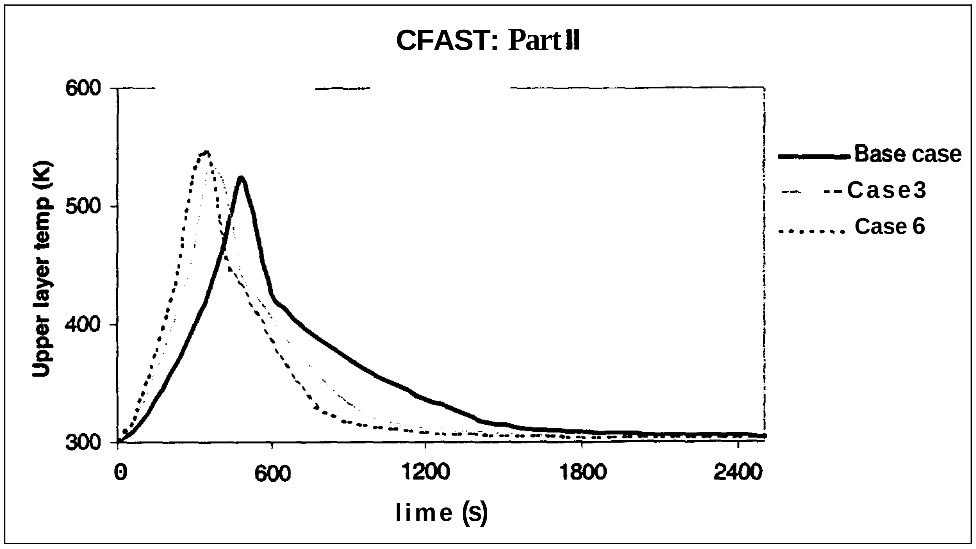



Figure 14 CFAST predictions of upper layer temperature in Part II

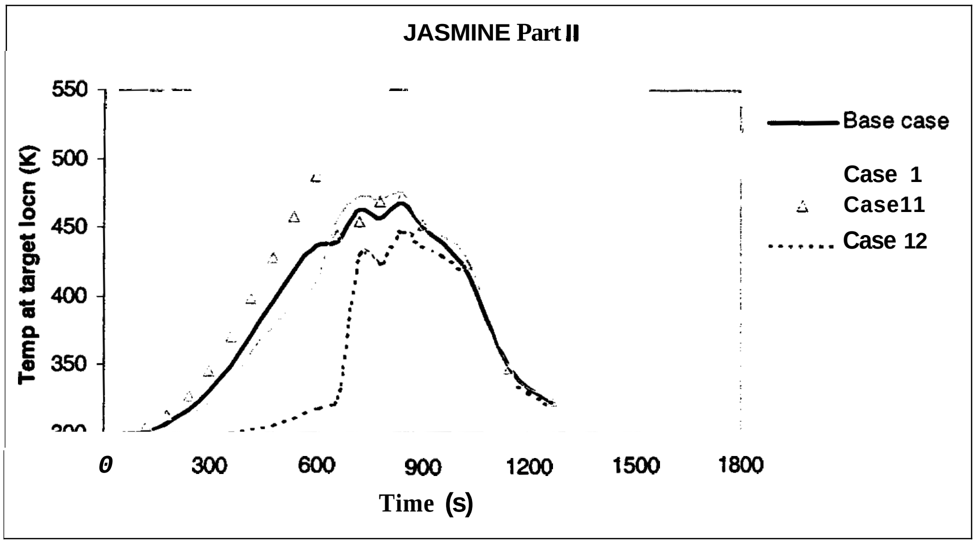



Figure 15 JASMINE predictions of gas temperatures in Part II

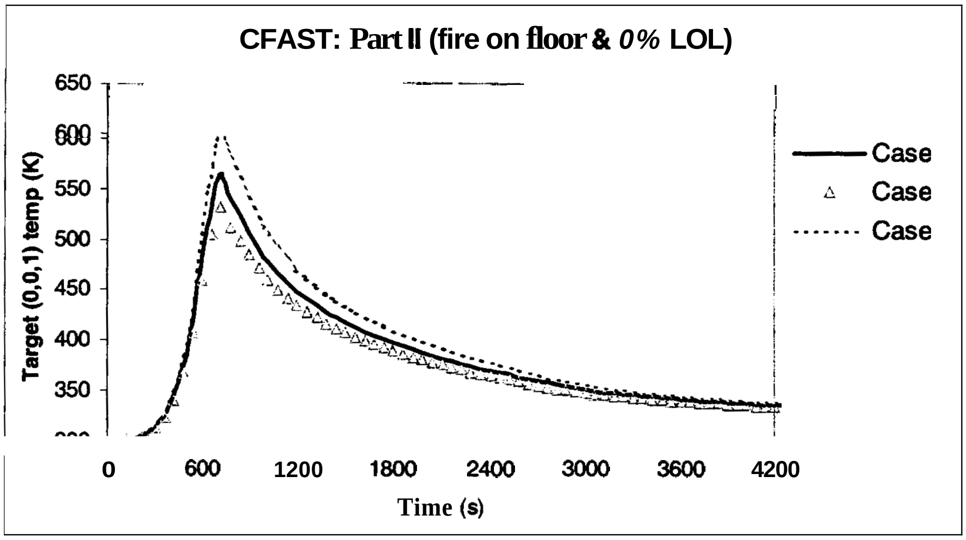



Figure 16 CFAST predictions of target temperatures in Part II

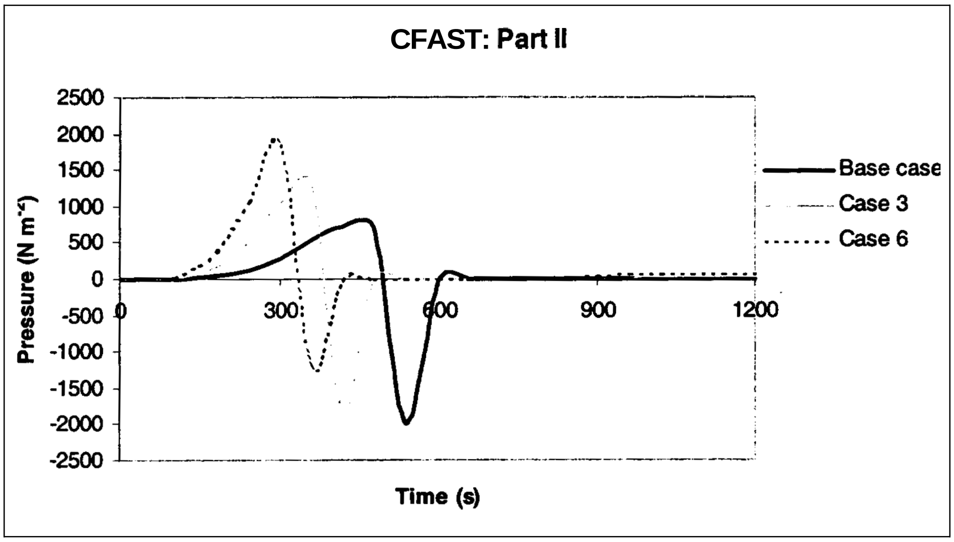



Figure 17 CFAST predictions of pressure in Part II

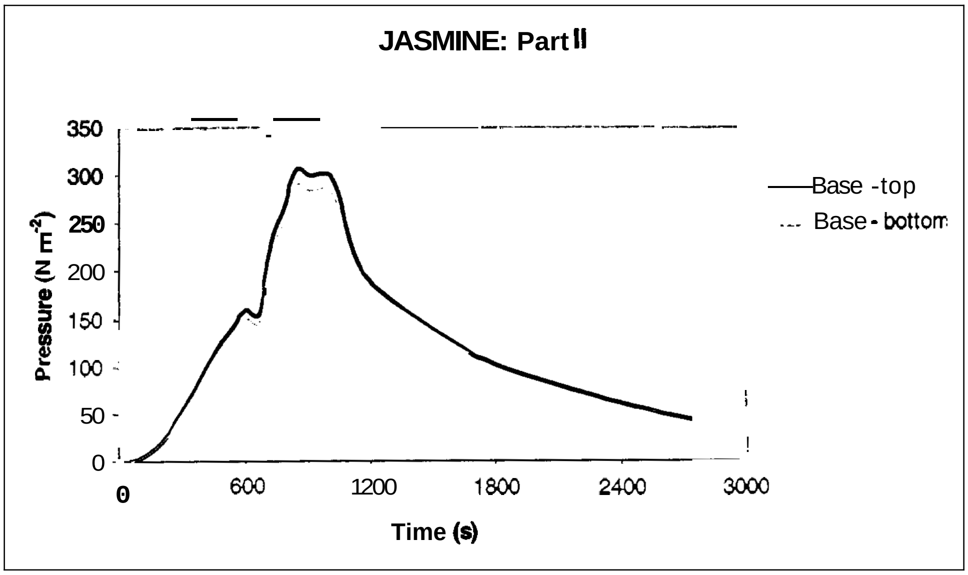



Figure 18 JASMINE predictions of pressure in Part II

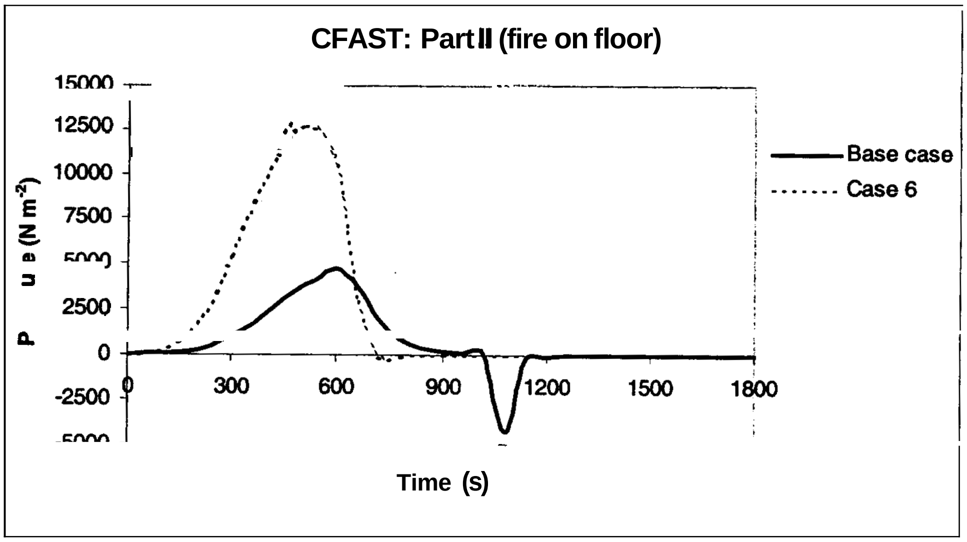



**Figure 19** CFAST predictions of pressure in Part II

## CONCLUDING REMARKS

BRE simulations of the benchmark exercise with JASMINE and CFAST indicate that target cable damage is unlikely for either Part I or Part II. In Part I this is a consequence of the small fire size, while for Part II with the bigger fires the effect of oxygen depletion was important. Although the temperatures predicted by JASMINE and CFAST were broadly similar, the pressure predictions for the door crack cases were not. For Part II the over-pressure differed by a factor of two, while in Part I the CFAST predicted over-pressures were a factor of ten or more greater than for JASMINE. There are assumptions made in both models that may have a bearing. However the issue has not been resolved yet, and requires further consideration.

Some other important issues remain, in particular in respect to modelling the fluxes to the cable targets and the heat conduction within the target. Further work is required in developing conduction models for cable type targets, and the task of modelling radiation from the flaming region and hot gas layer to the target needs to be considered more carefully. Here the use of CFD models, in combination with appropriate radiation models, may offer significant benefit. Furthermore, to address properly the hazard associated with cable tray fires, some form of fire growth/spread model may be required. The assumption that the entire length of cable tray burns from the start of the fire under-estimates the potential the potential thermal damage to the target cable during the growing stage of the fire.

Although the results of the benchmark exercise would seem to provide confidence in using either zone or CFD models to that type of scenario, it is felt that the problem of 'nearly-sealed' compartments needs further thought. The particular cases studied may have masked the potential problems associated with such scenarios since other effects such as oxygen depletion were here more important. However, in another situation the degree of pressure build-up, and the associated venting and reverse-venting of air, may be more crucial.

The next stage of the collaborative project will need to consider more carefully the limits of fire models for other types of scenario. Here, issues such as the limitation of zone models for very large or complex geometries, or the presence of complex mechanical ventilation systems, need addressing.

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